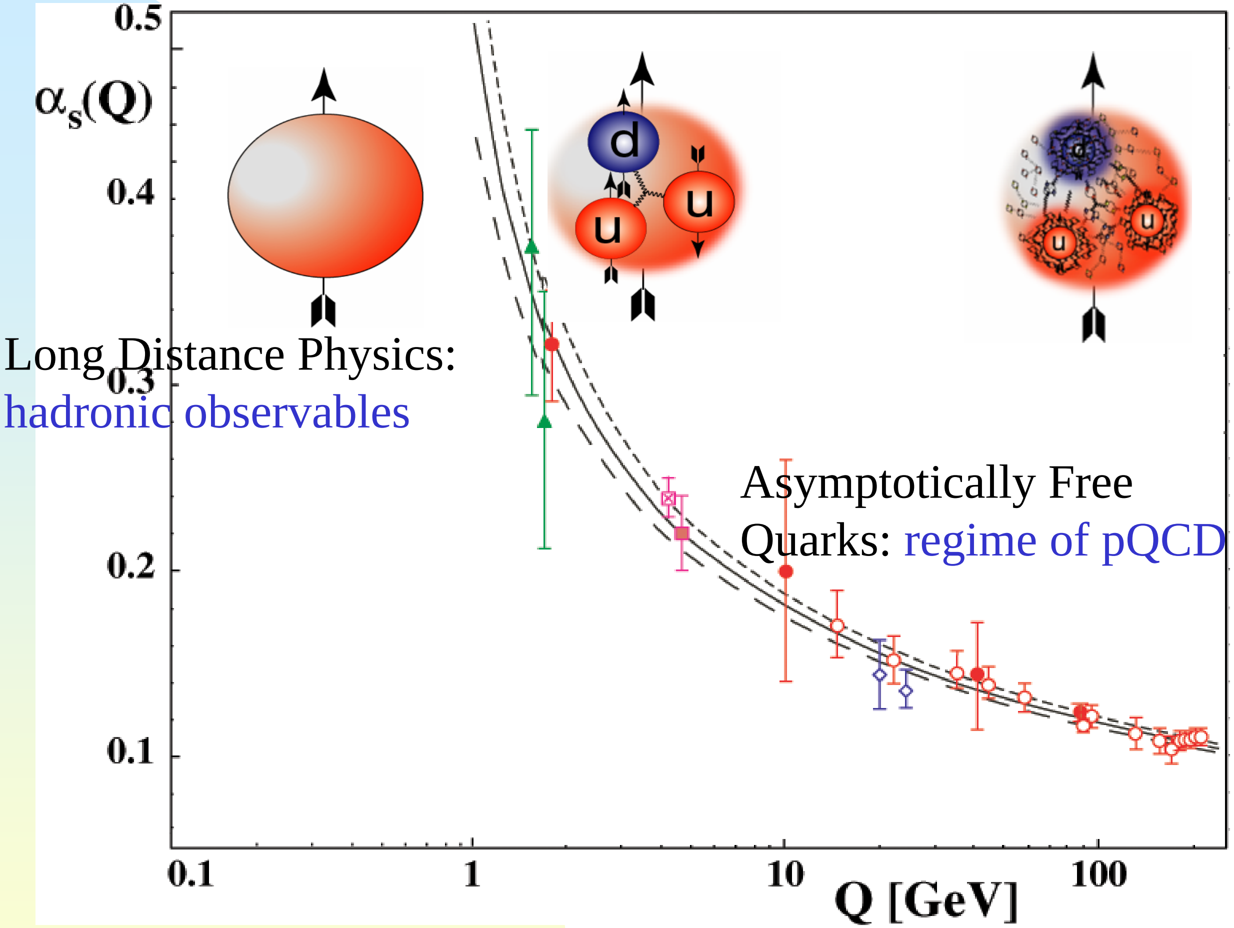
Duality and the Transition to Perturbative QCD



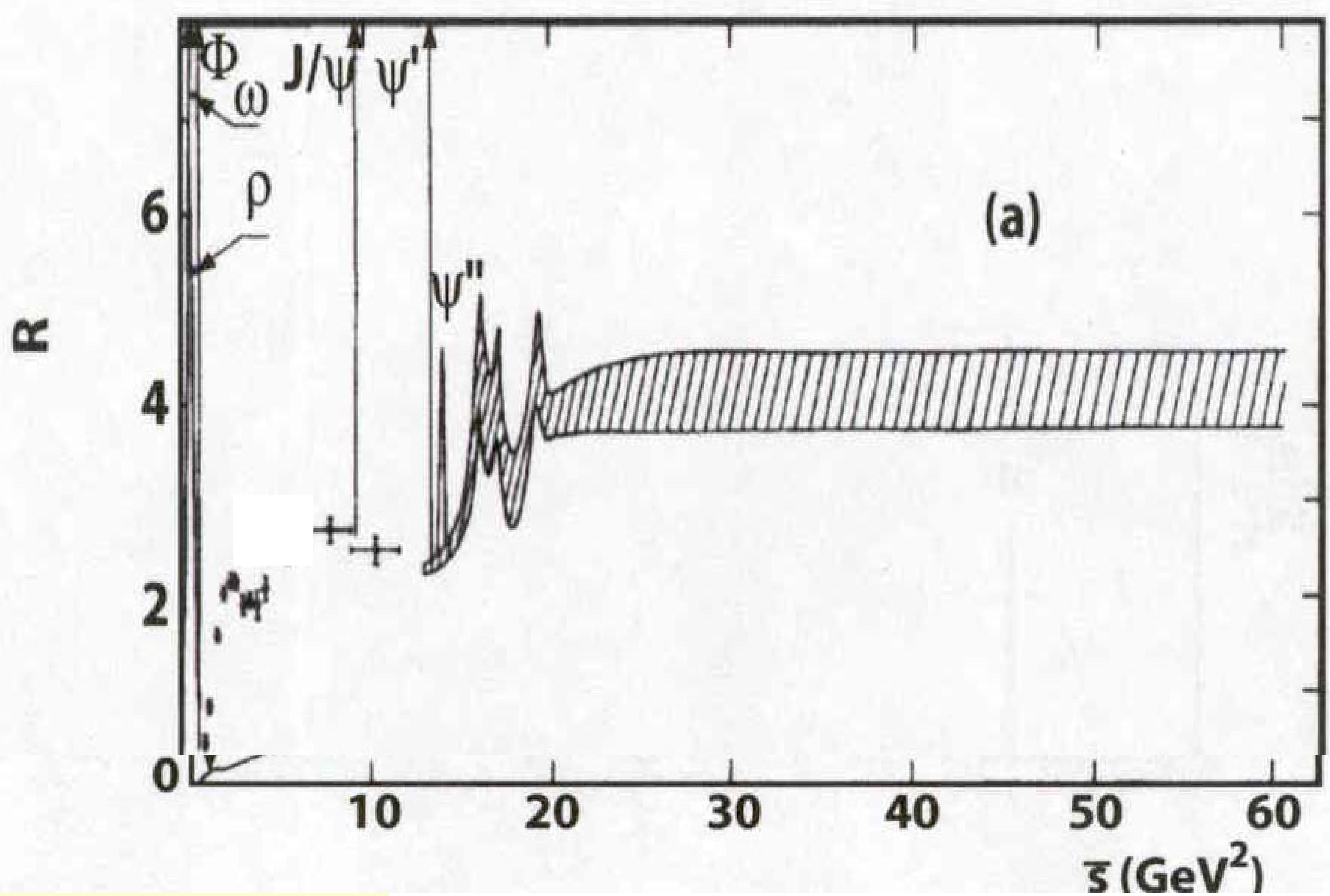
Asymptotically the photon couples to quarks, yet *confinement* ensures that only hadronic final states are observed.

Duality is intimately related to the transition from soft to hard QCD.

Textbook Example: $e^+e^- \longrightarrow$ hadrons

$$R = \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$\lim_{E\to\infty} \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q e_q^2$$



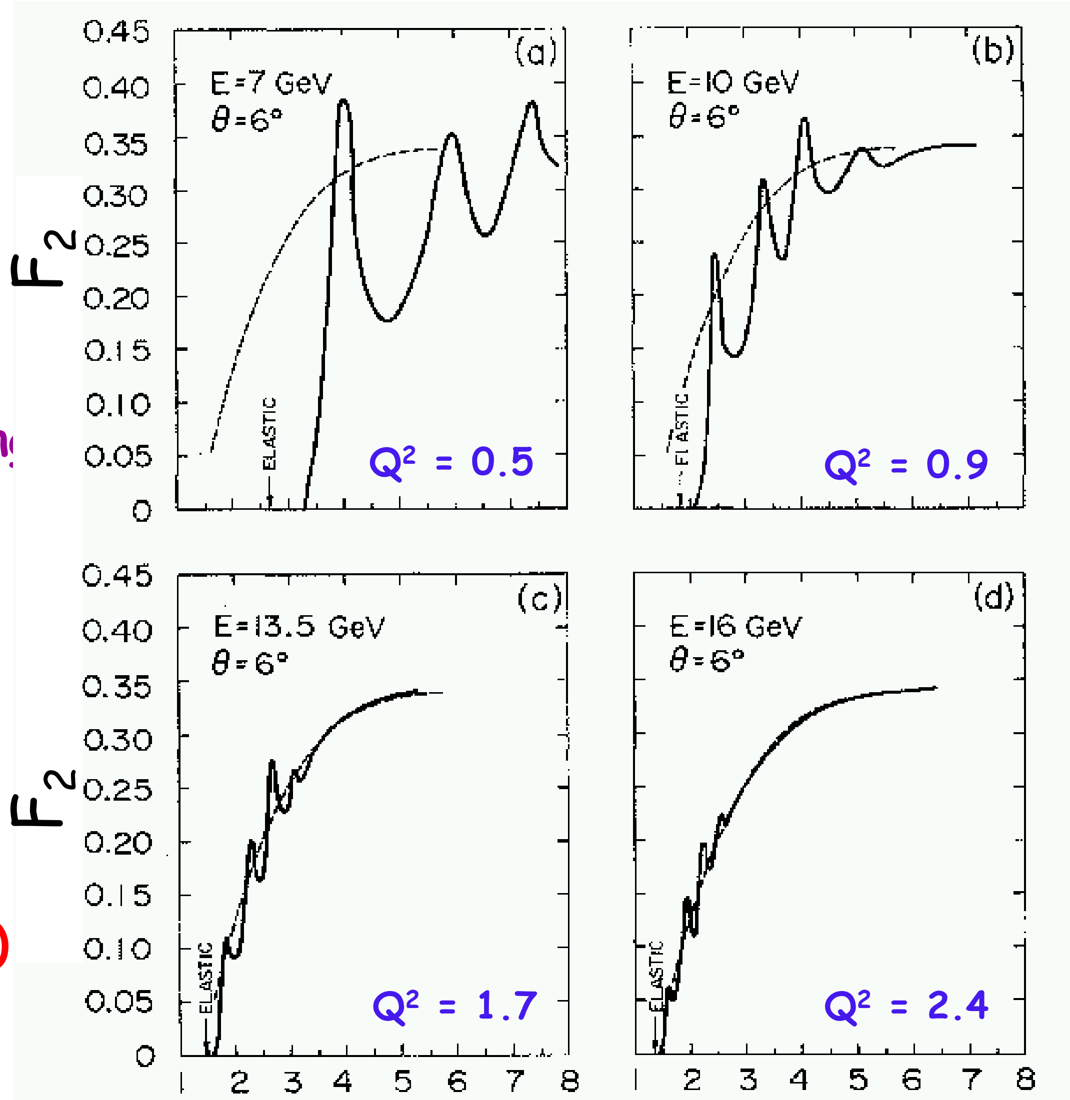
Only evidence of hadrons produced is narrow states oscillating around step function determined by quark color, charge.

Bloom-Gilman Duality

- First observed ~1970 by Bloom and Gilman at SLAC by comparing resonance production data with deep inelastic scattering data using ad hoc variable
- Integrated F_2 strength in nucleon resonance region equals strength under scaling curve.
- Resonances oscillate around curve at all Q^2

Shortcomings:

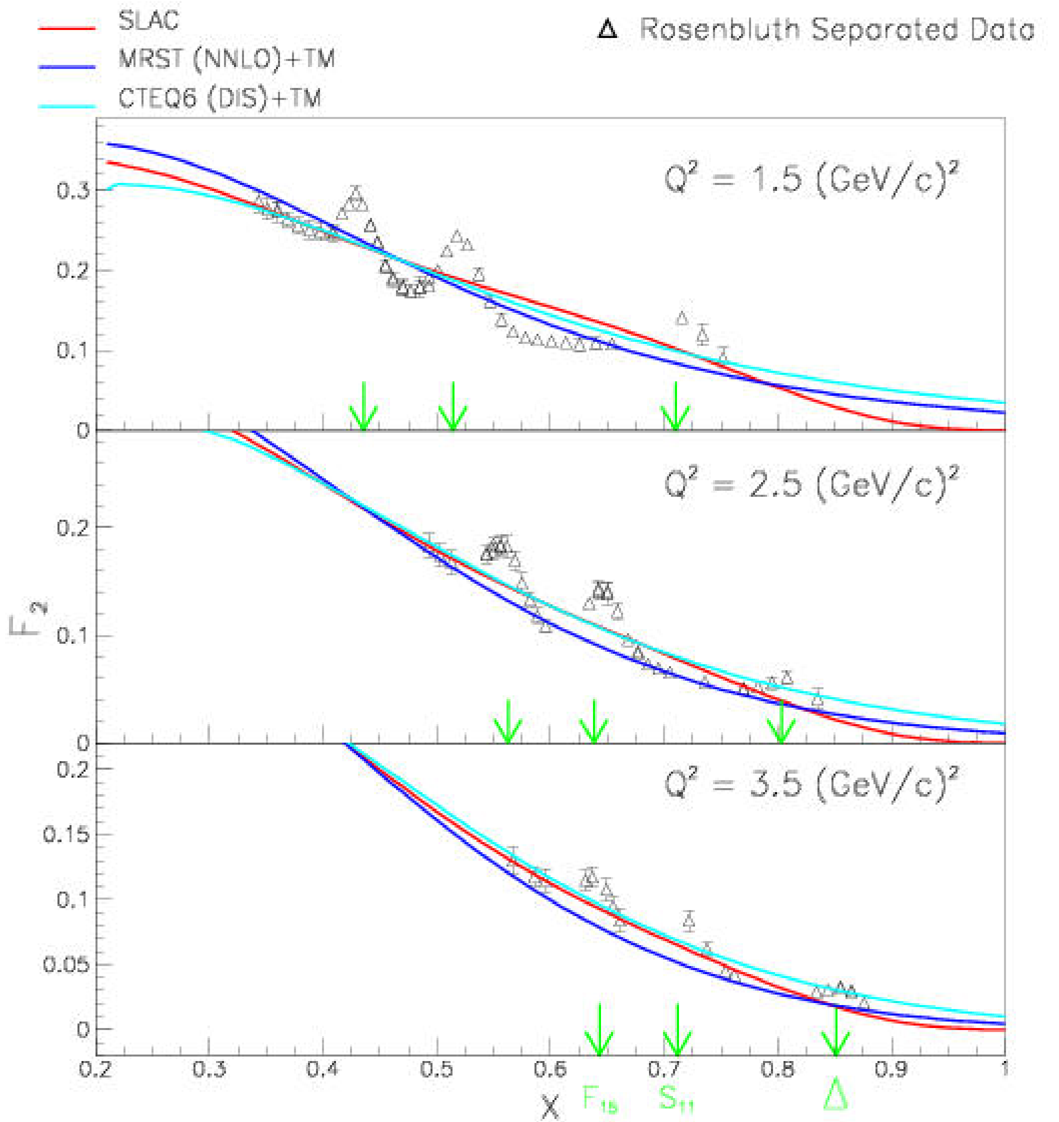
- Only a single scaling curve and no Q^2 evolution (theory inadequate in pre-QCD era)
- No σ_L/σ_T separation → F_2 data depend on assumption of $R = \sigma_L/\sigma_T$
- Only moderate statistics



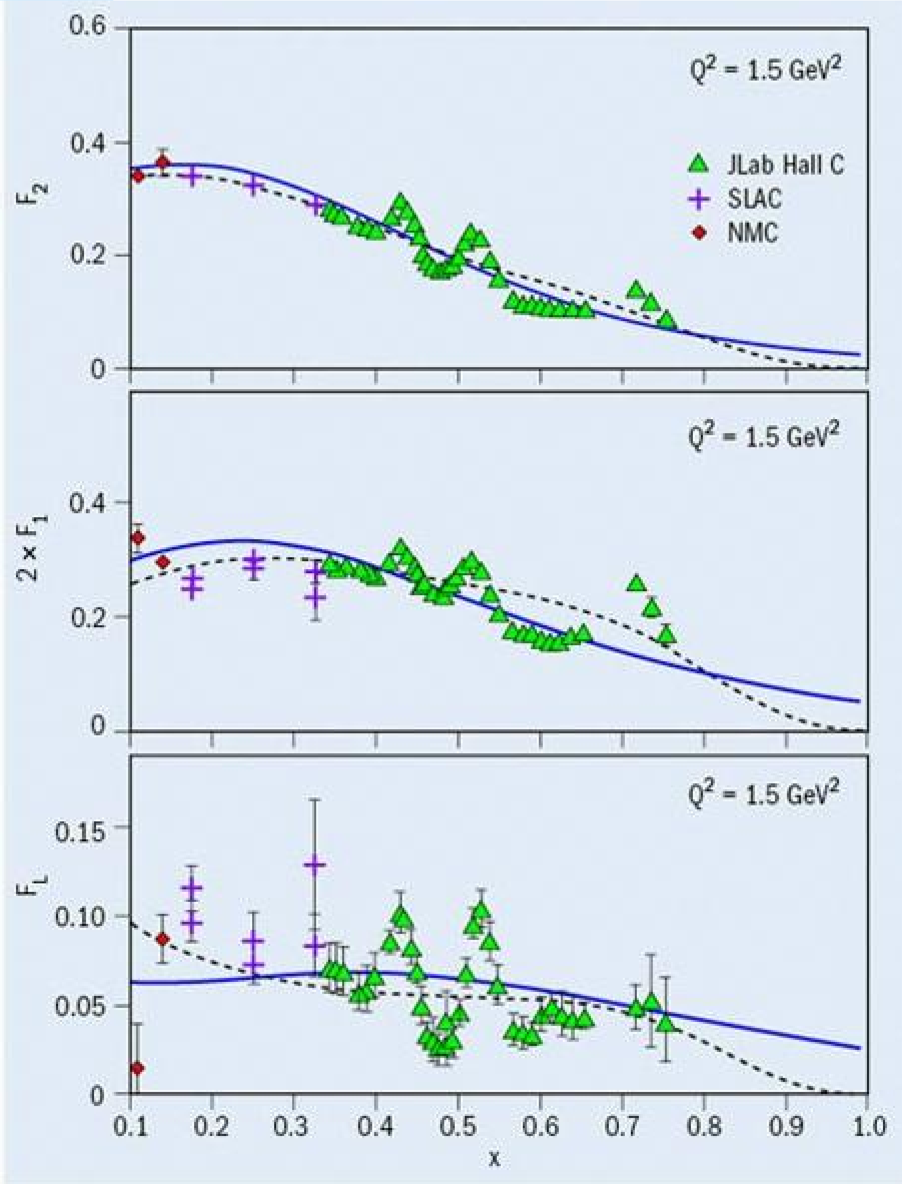
$\omega' = 1+W^2/Q^2$

Bloom-Gilman Duality in F_2 Today

- F_2 DIS well-measured over several orders of magnitude in x, Q^2
- QCD established theory
- Perturbative predictions (based on extracted PDF's, evolution) available
- Quark-Hadron Duality quantifiable (more later….)
- *Show to hold to better than 5% above Q^2 ~ 0.5 GeV^2*



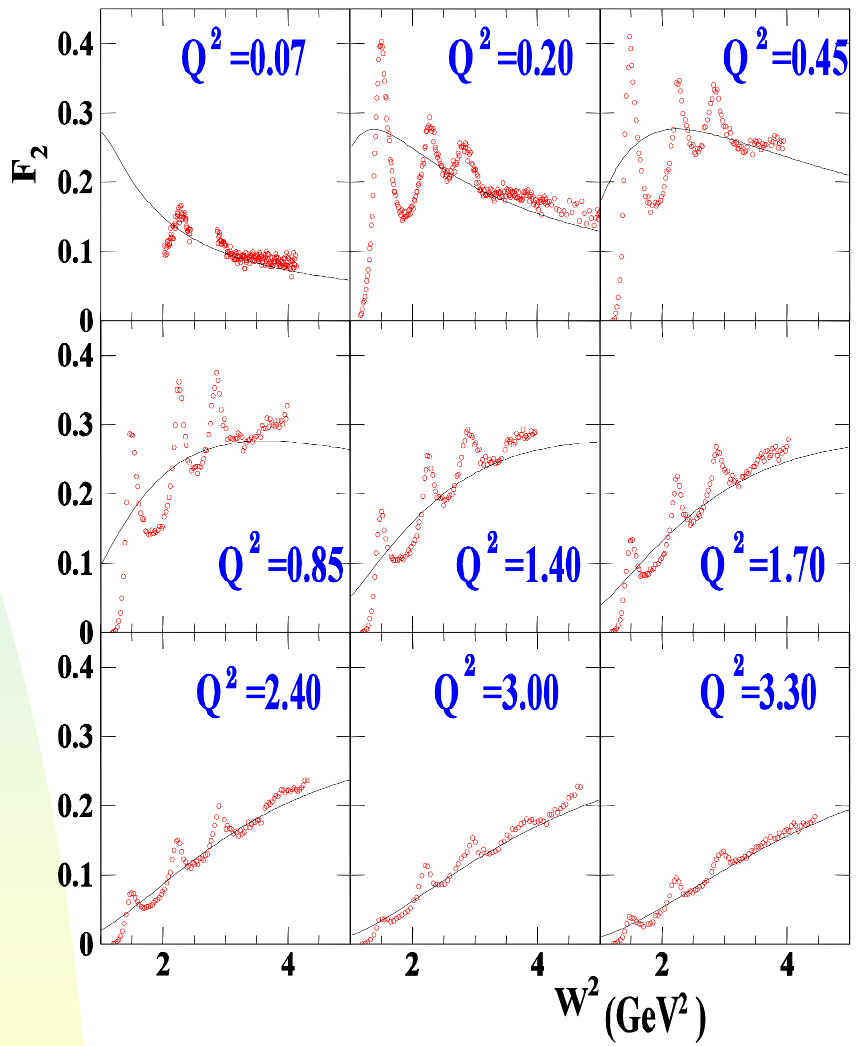
E94-110 : Precise Measurement of Separated Structure Functions in Nucleon Resonance Region



- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small.
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron transition.
- This explains the success of the parton model at relatively low W^2 (=4 GeV^2) and Q^2 (=1 GeV^2).

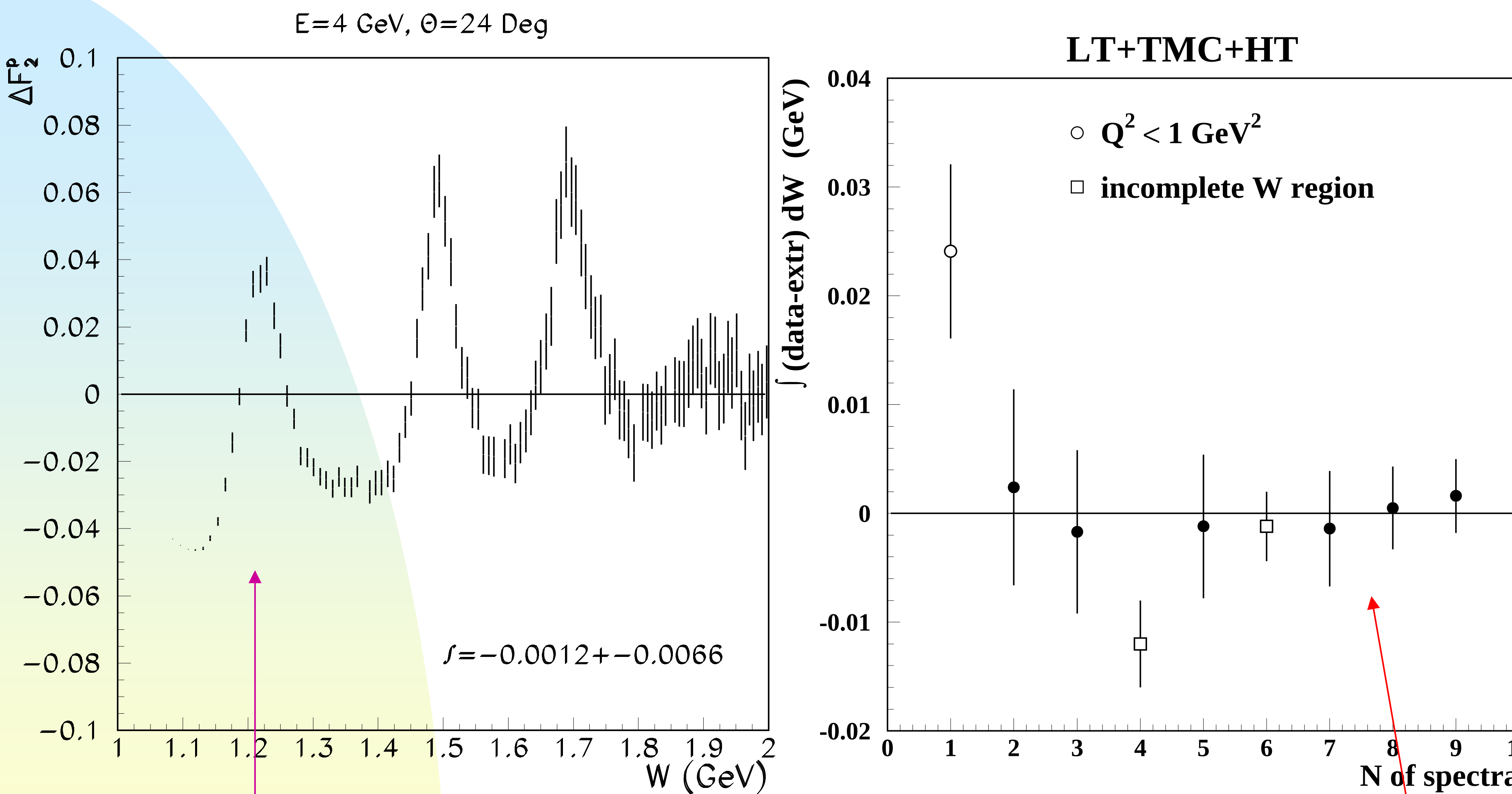
"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."
(CERN Courier, December 2004)

Bloom-Gilman Duality in F_2 Today



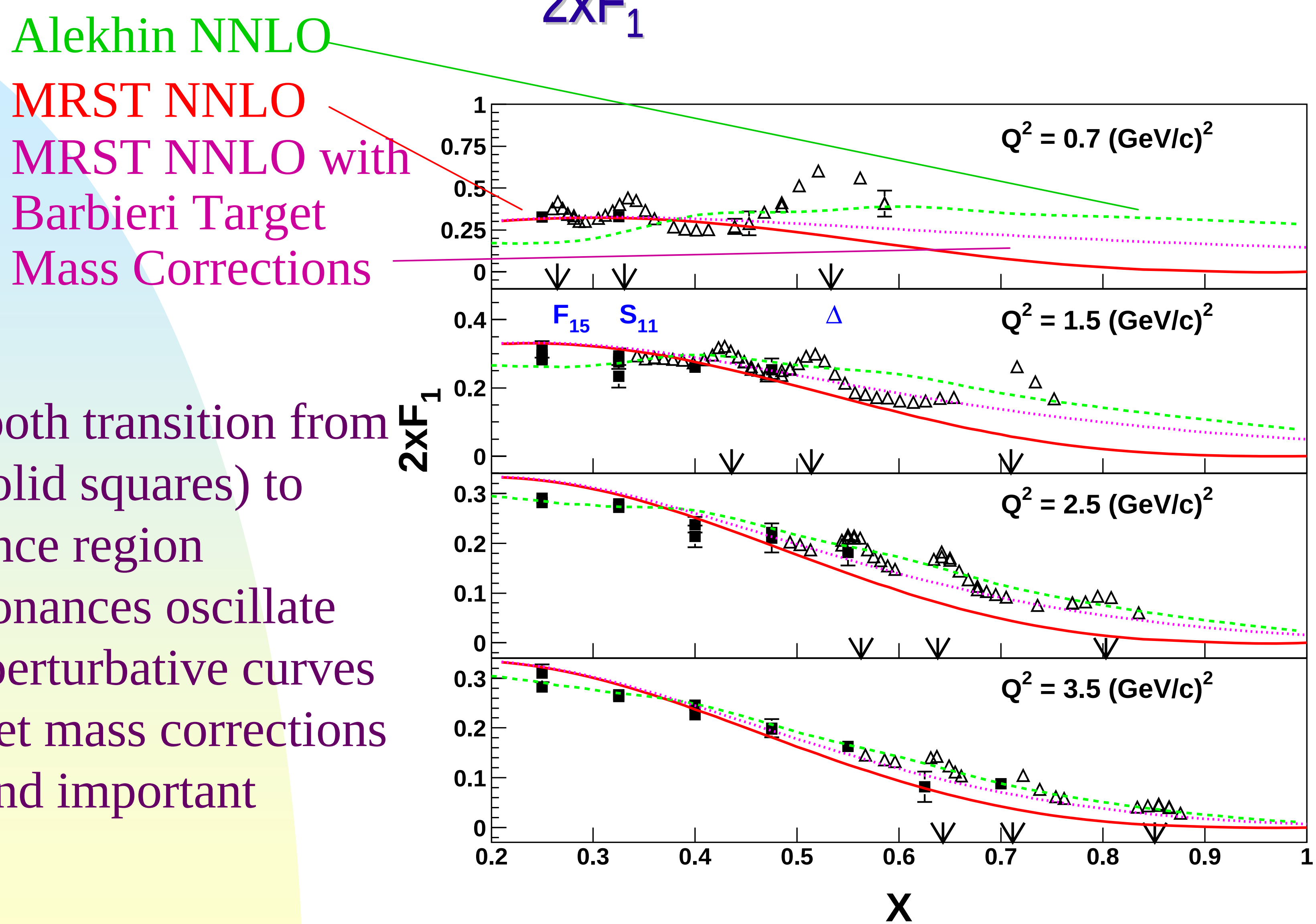
The scaling curve determines the Q^2 behavior of the resonances! … or … the resonances "fix" the scaling curve!

Bloom-Gilman Duality in F_2 Today



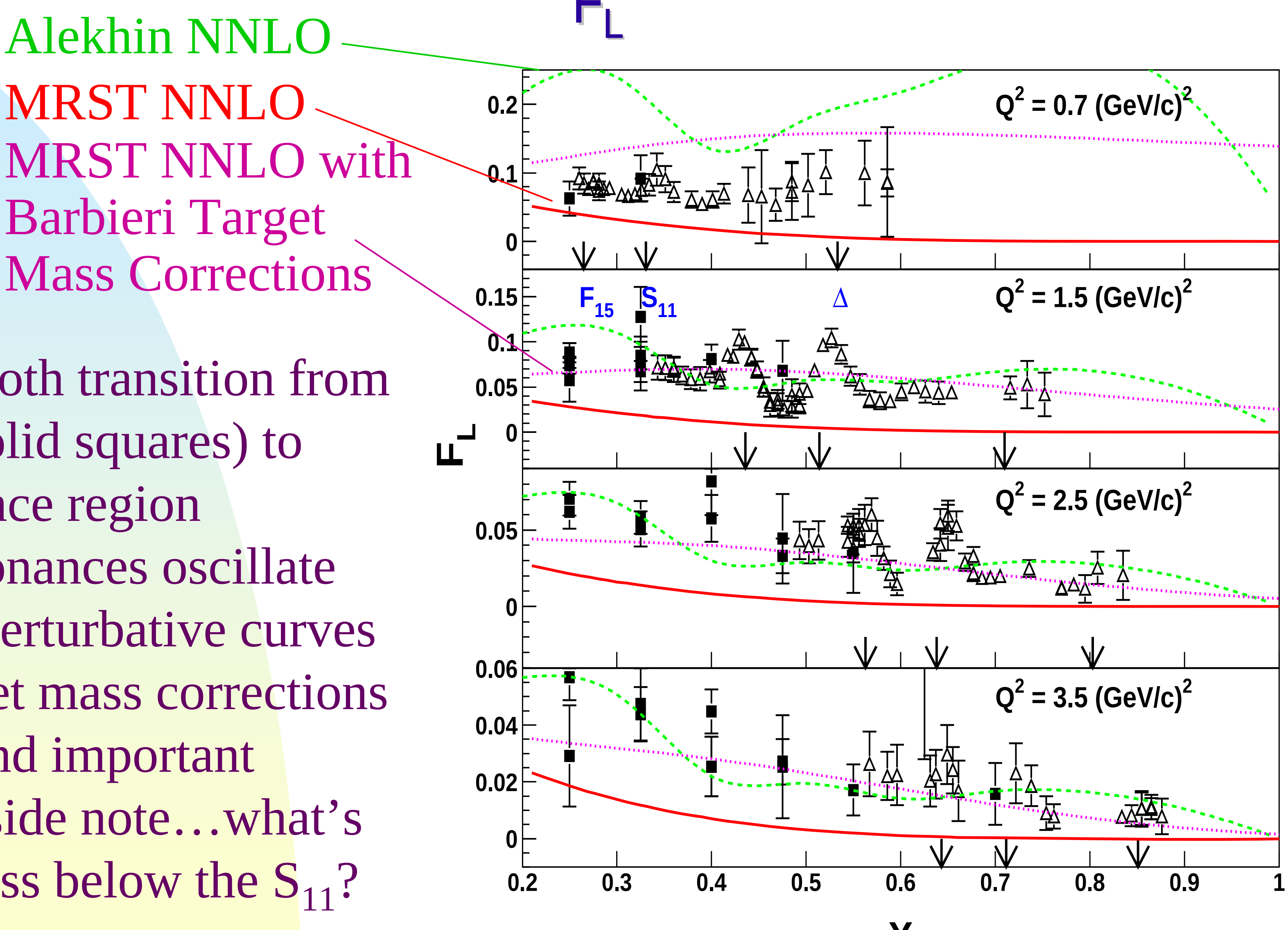
Difference between Alekhin NNLO curve (formed from lepton-nucleon scattering only) and resonance data, *integrated for many spectra*

Experimental Status of L/T Separated Structure Functions: $2xF_1$



- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves
- Target mass corrections large and important

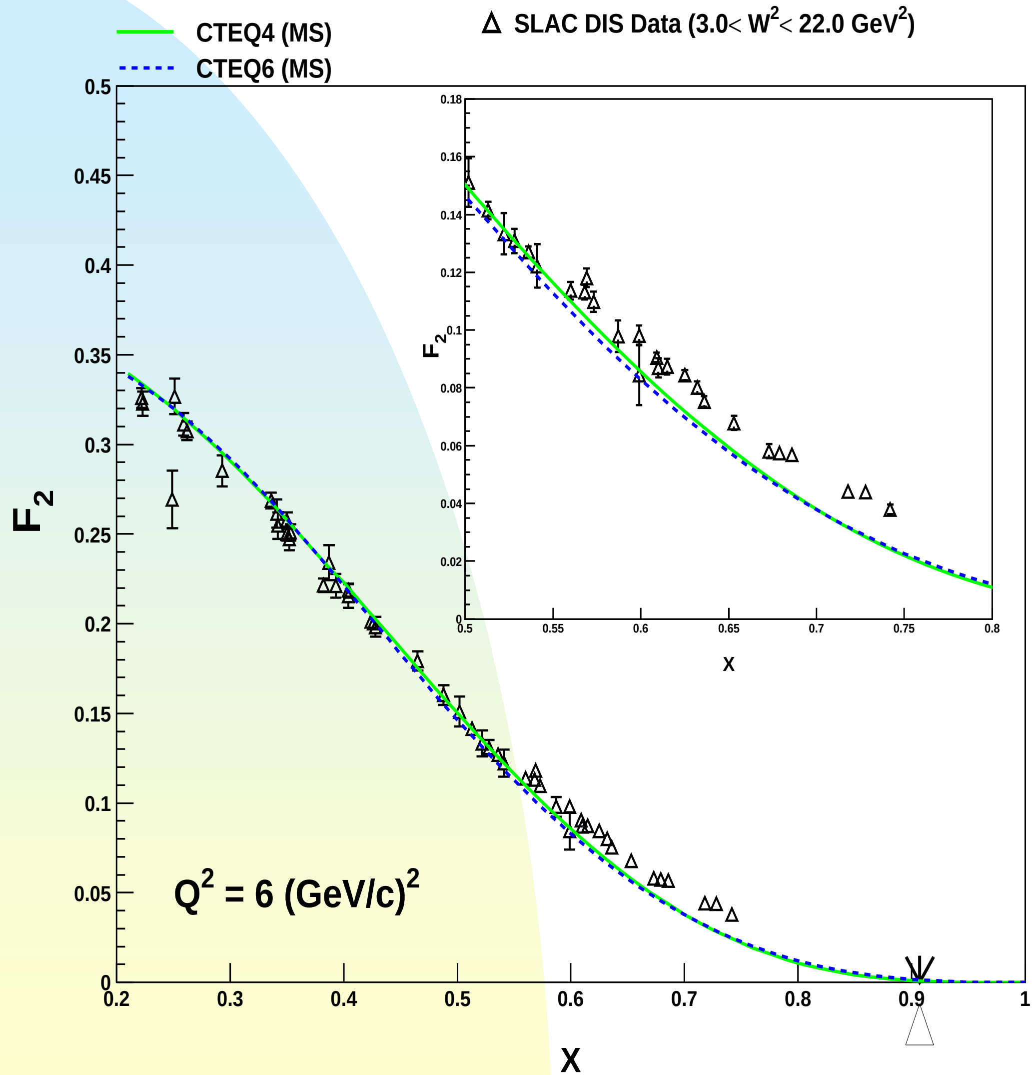
Experimental Status of L/T Separated Structure Functions: F_L

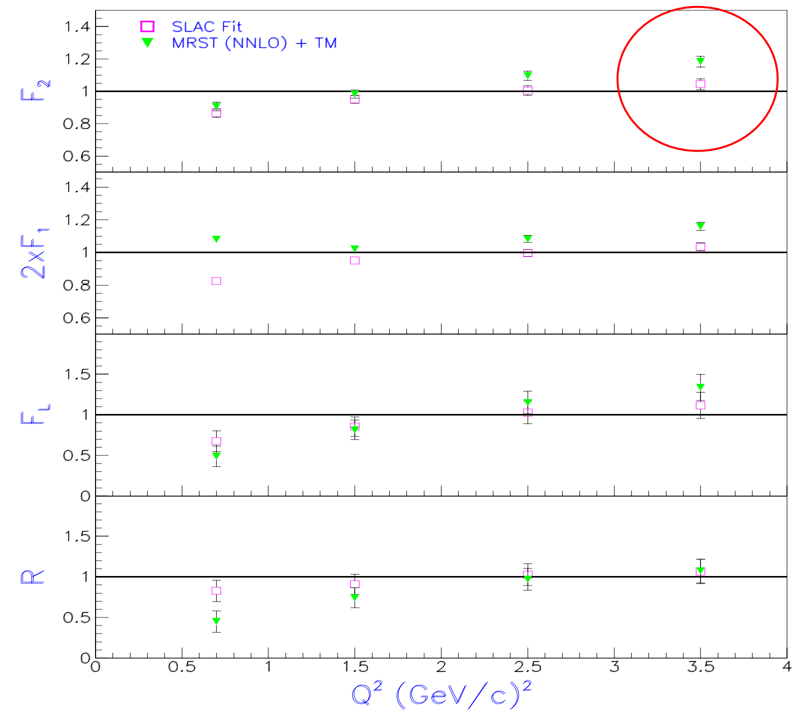


- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves
- Target mass corrections large and important
- Fun side note…what's that mass below the S_{11}?

Hall C E94-110 publication submitted

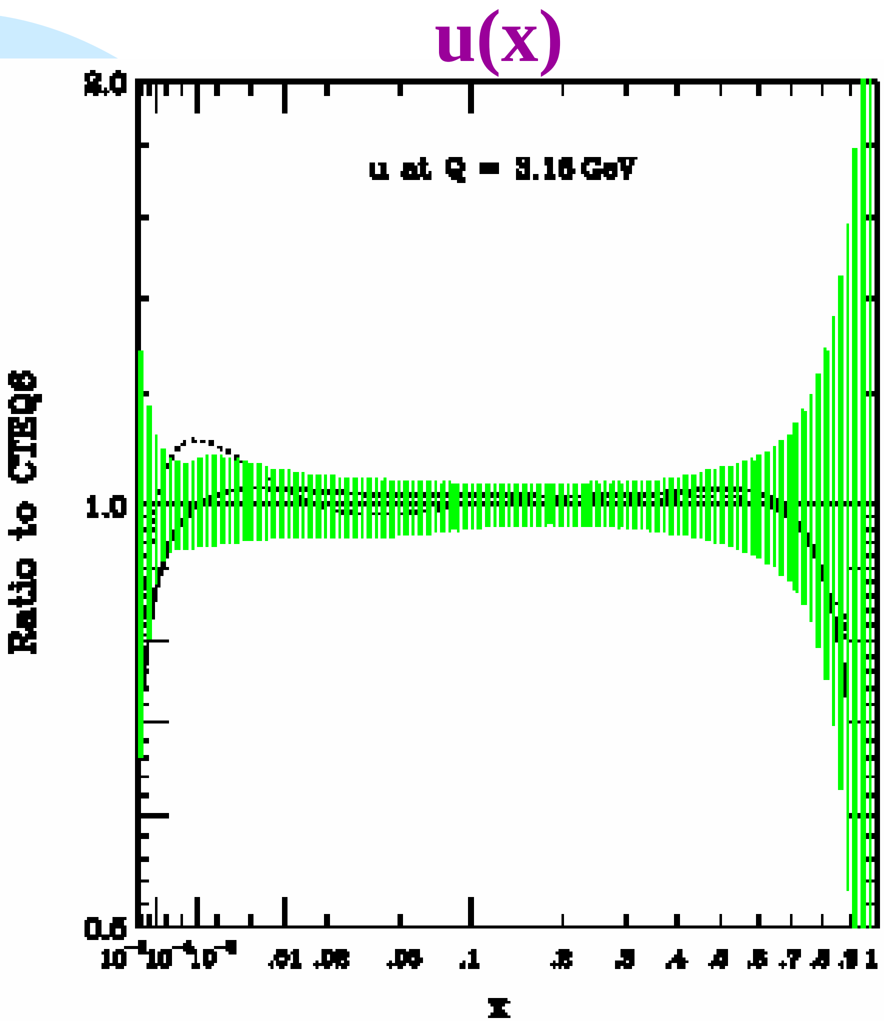
Quantification - How to do it?

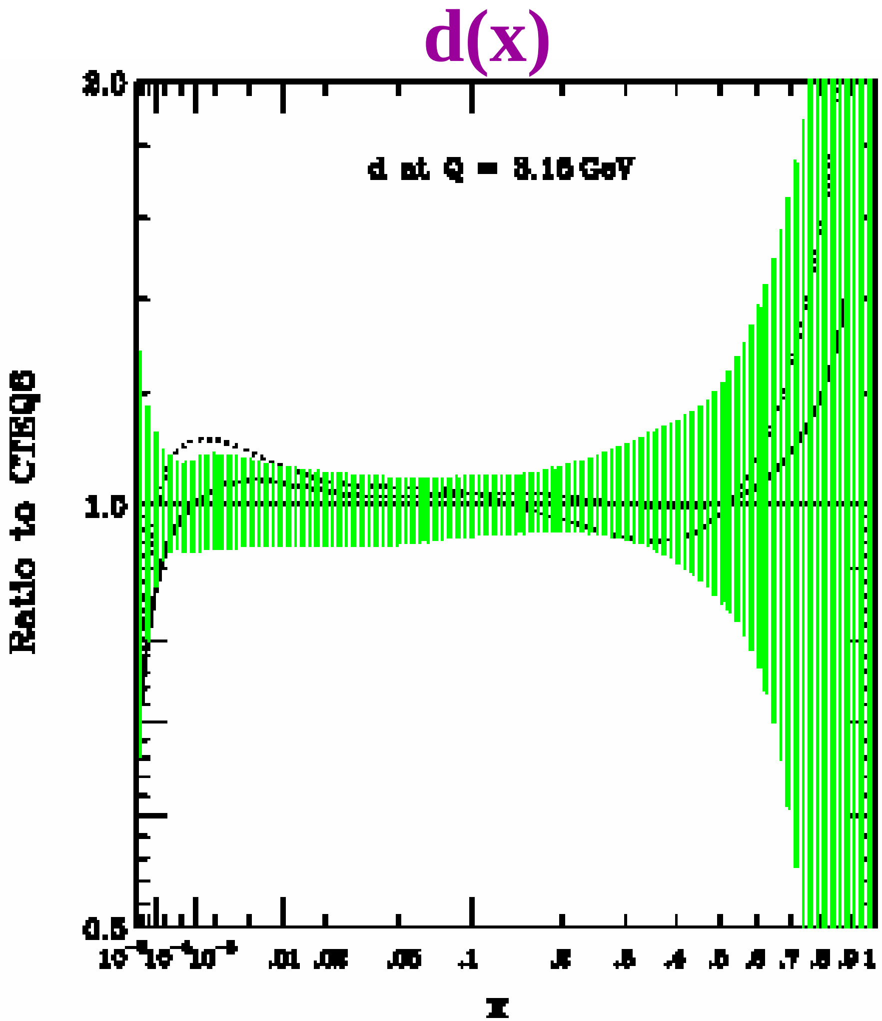




Comparisons of PDF-based parameterizations to data at large x is not a resonance regime issue alone!....

Parton Distribution Functions





PDF's by far least well known at large x – poses a problem for duality quantification, ***and an opportunity (USE duality for large x regime!)***

Duality in pQCD

- Moments of the Structure Function

$$M_n(Q^2) = \int_0^1 dx\, x^{n-2} F(x,Q^2)$$

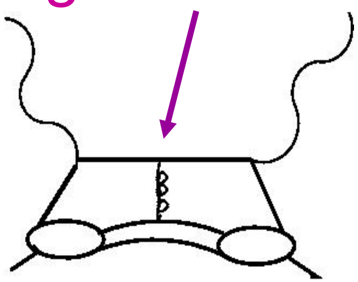
If n = 2, this is the Bloom-Gilman duality integral!

- Operator Product Expansion

$$M_n(Q^2) = \sum_{k=1}^{\infty} (nM_0^2/\, Q^2)^{k-1}\, B_{nk}(Q^2)$$

higher twist logarithmic dependence

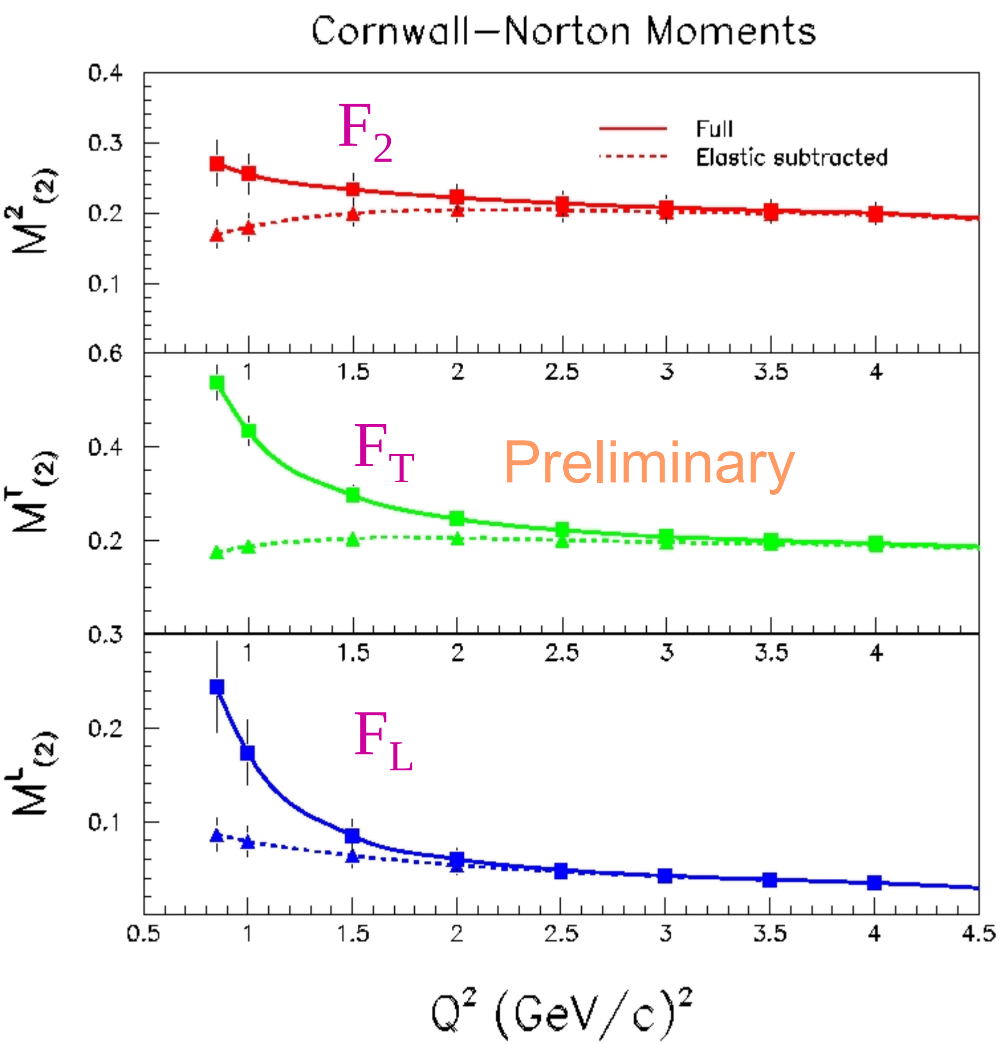
(pQCD)



- Duality is described in the Operator Product Expansion *as higher twist effects being small or cancelling* **DeRujula, Georgi, Politzer (1977)**

n = 2 Cornwall-Norton Moments

DIS: SLAC+NMC
RES: E94-110



Elastic Contributions

$$F_T^{EL} = G_M^2\,\delta(x-1)$$

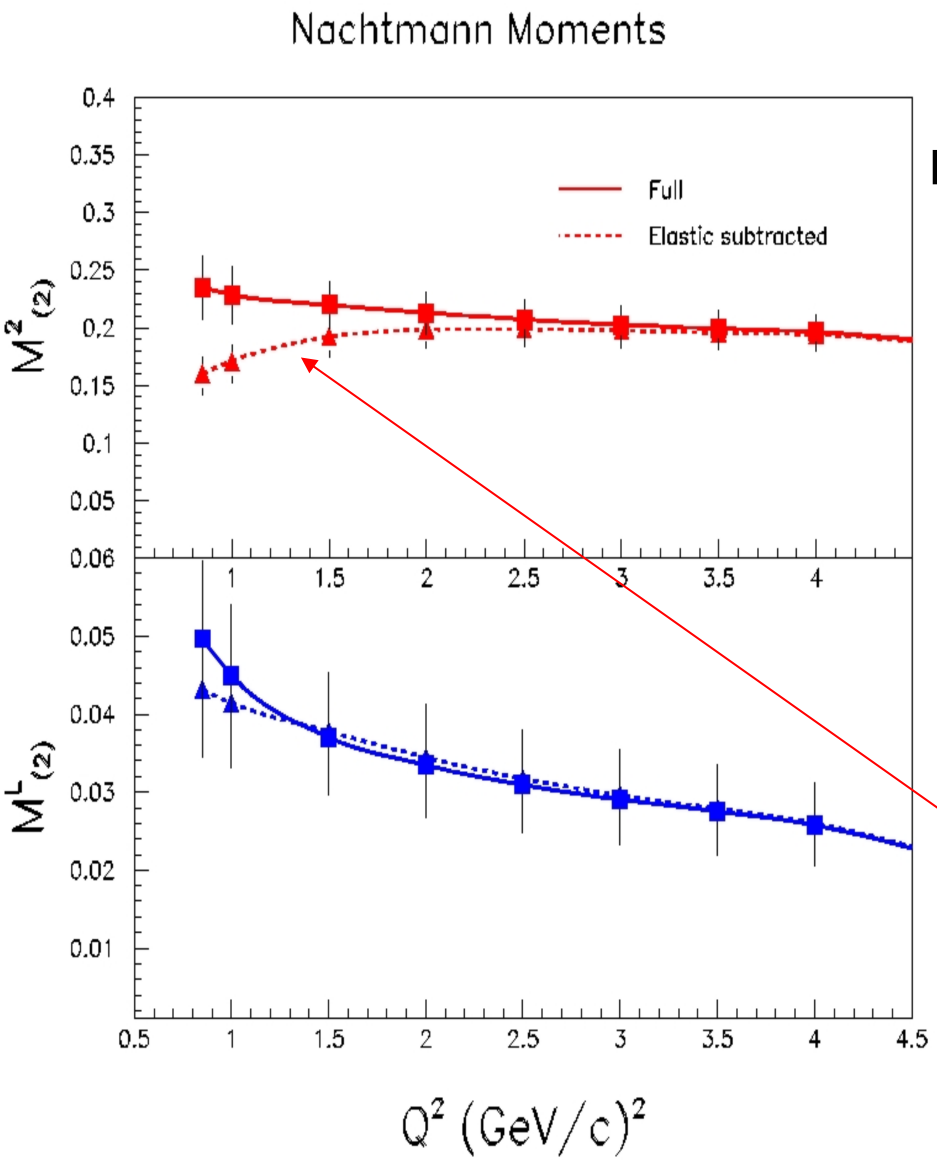
$$F_2^{EL} = \frac{(G_E^2 + \tau G_M^2)\,\delta(x-1)}{1+\tau}$$

$$\tau = q^2/4M_p^2$$

$$F_L^{EL} = G_E^2\,\delta(x-1)$$

perturbative Q^2 dependence: small or cancelling higher twist! - not true for contributions from the elastic peak (bound quarks)

n = 2 Nachtmann Moments



Momentum sum rule

$$M_L^{(n)} = \alpha_s(Q^2)\left\{ \frac{4M_2^{(n)}}{3(n+1)} + \frac{2c\int dx\, xG(x,Q^2)}{(n+1)(n+2)} \right\}$$

Gluon distributions!

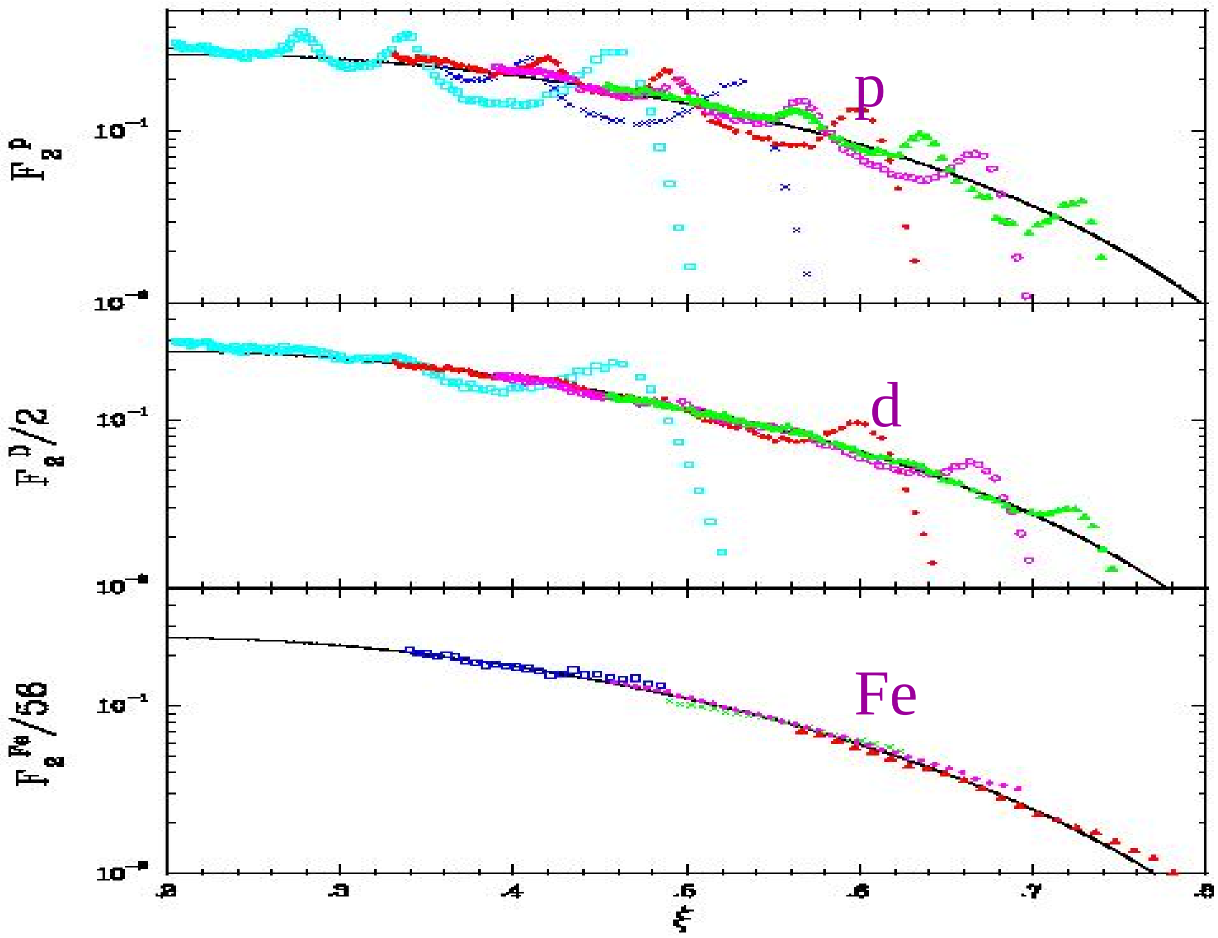
This sum rule is only at leading twist. Data must be corrected for target mass effects (use Nachtmann moments). They work well!

$$\xi = 2x[1 + (1 + 4M^2x^2/Q^2)^{1/2}]$$

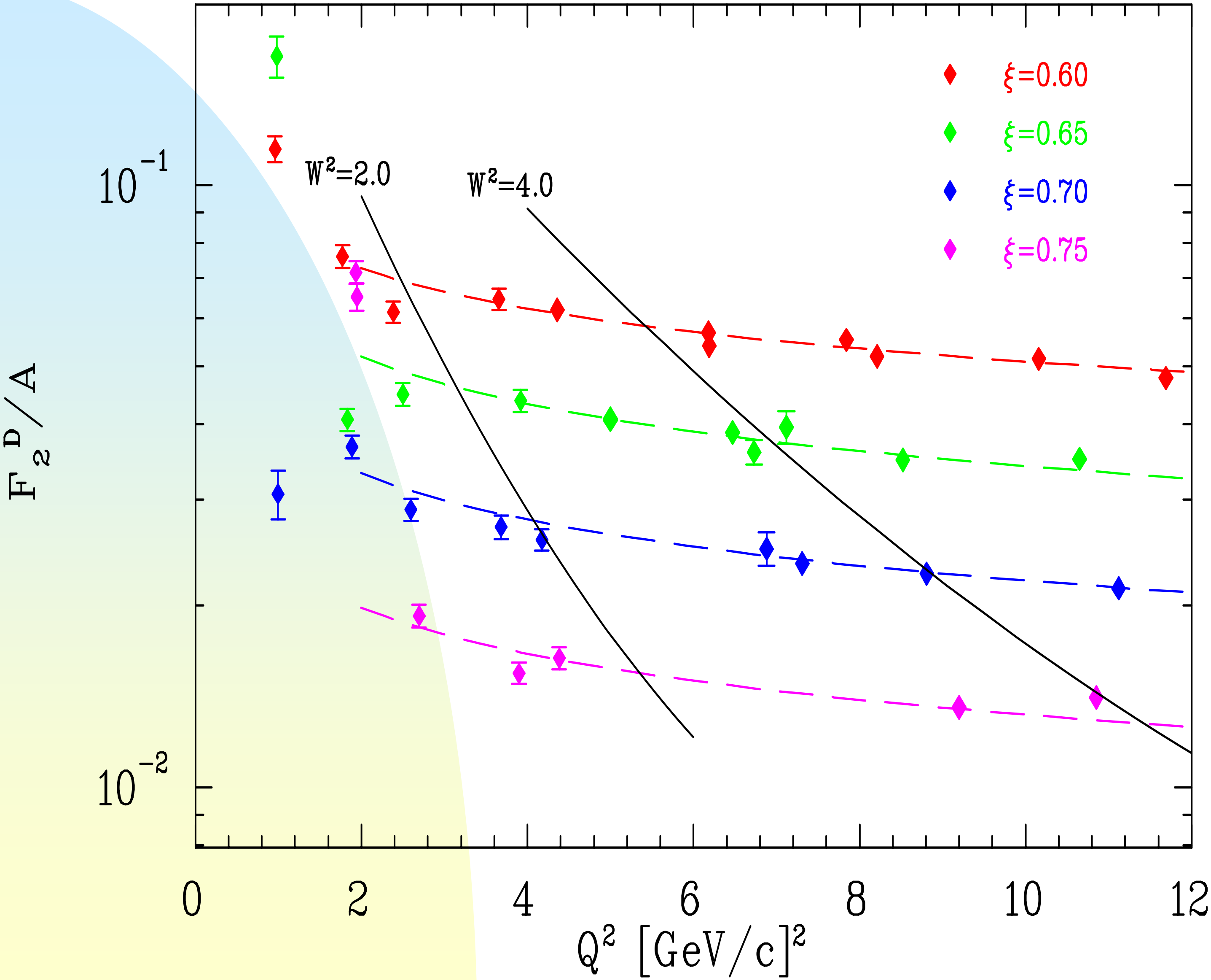
Duality in Nuclei, Too! (F_2)

$$\xi = 2x\left[1 + (1 + 4M^2x^2/Q^2)^{1/2}\right]$$

- Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2
- GRV curve
- The nucleus does the averaging
- For larger A, resonance region indistinguishable from DIS



Duality (F_2) in Deuterium

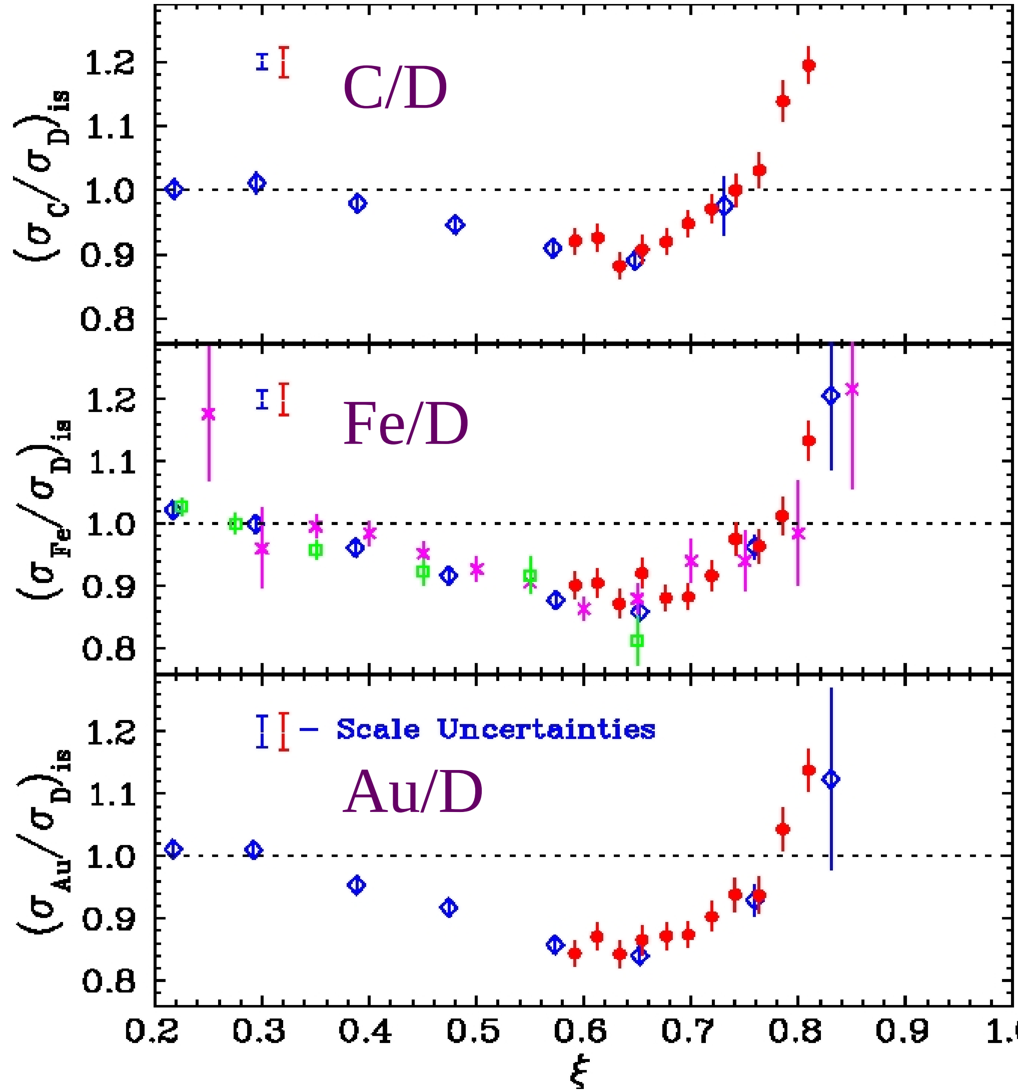


Resonance region and DIS F_2 same, with same Q^2 dependence, other than at smallest W

Duality and the EMC Effect

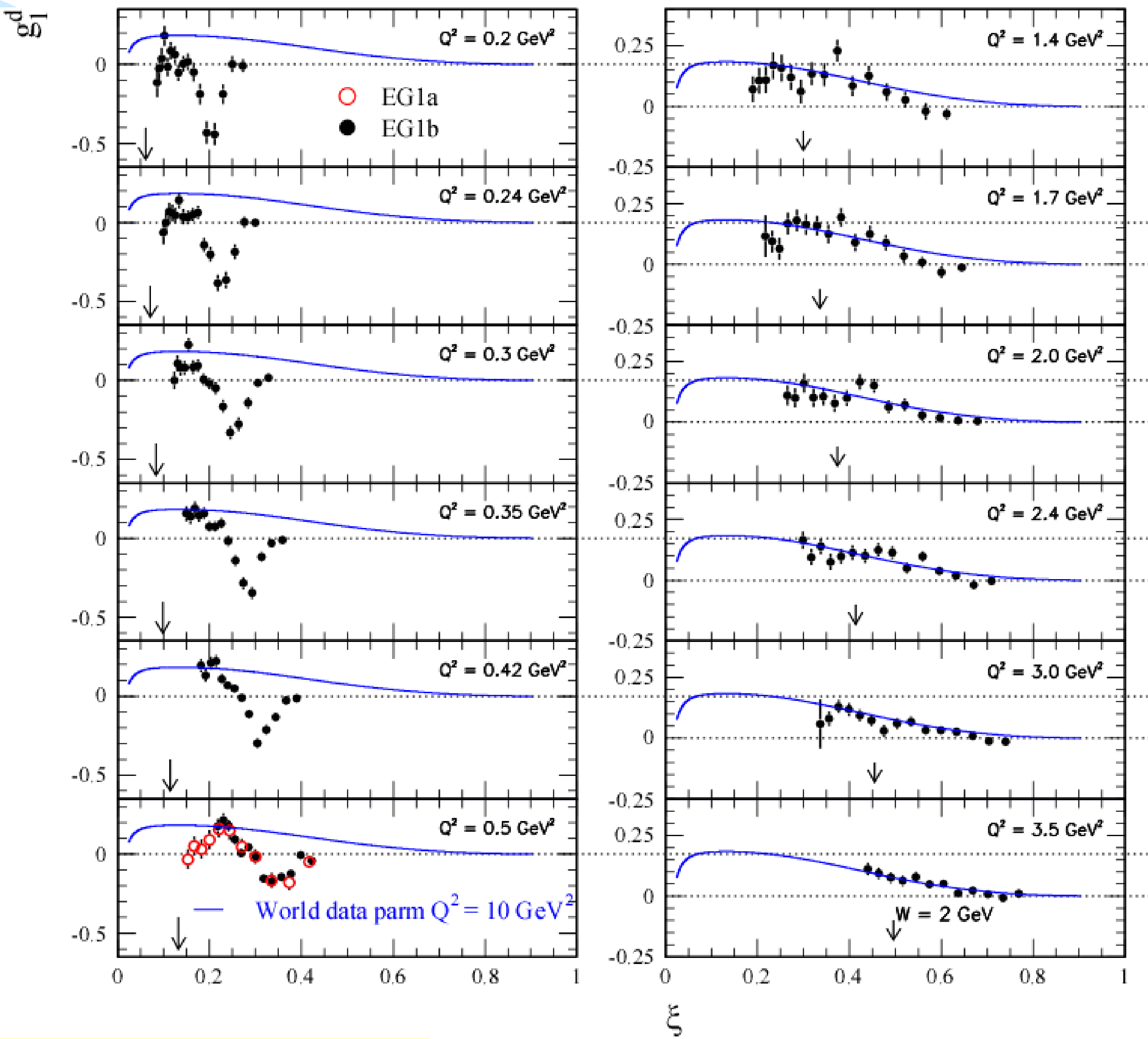
Medium modifications to the structure functions are the same in the resonance region as in the DIS

Rather surprising (deltas in nuclei, etc.)



J. Arrington, et al., submitted

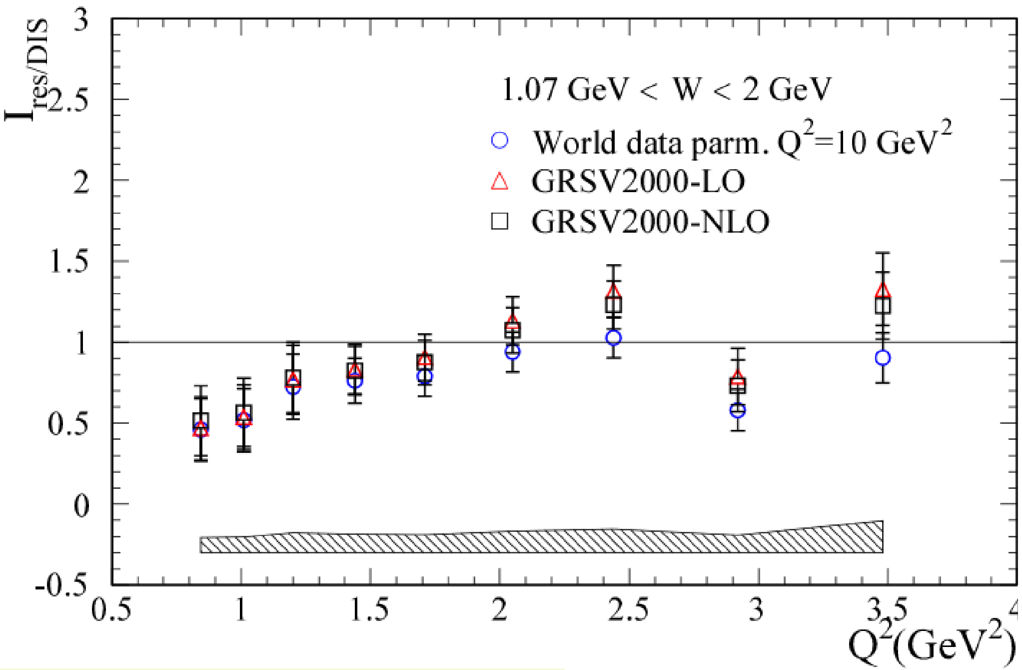
Duality in g_1^d (from T. Forest et al., Hall B EG1)

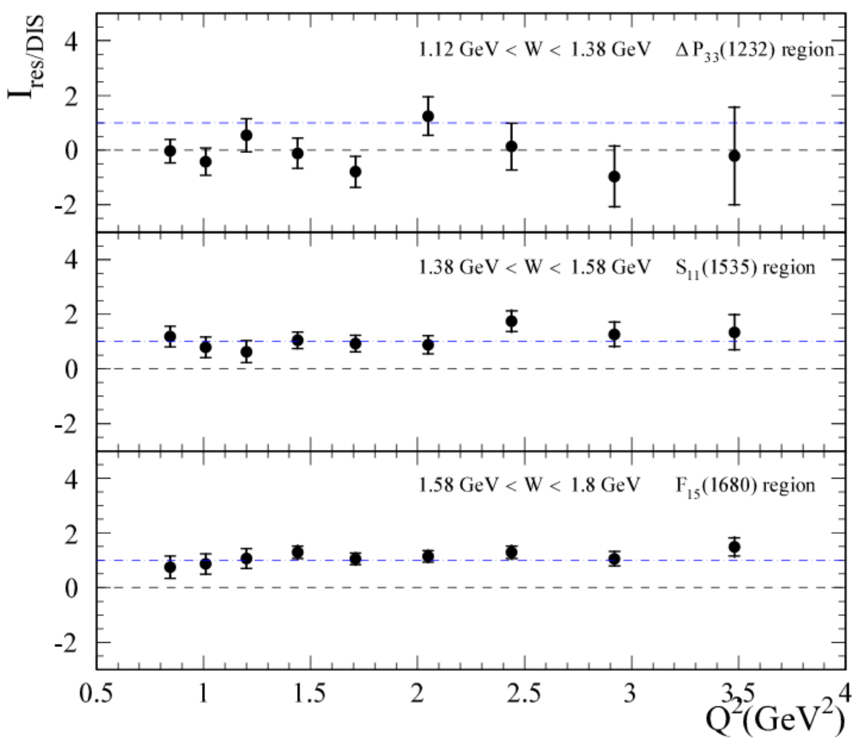


Like F2, g1 in the resonance region wiggles around high-Q2 curve curve. Strong deviation in region of Delta(1232).

The 2.5 and 4.2 GeV data will clarify the intermediate Q^2 range

Spin Structure Functions, g_1^d (continued)



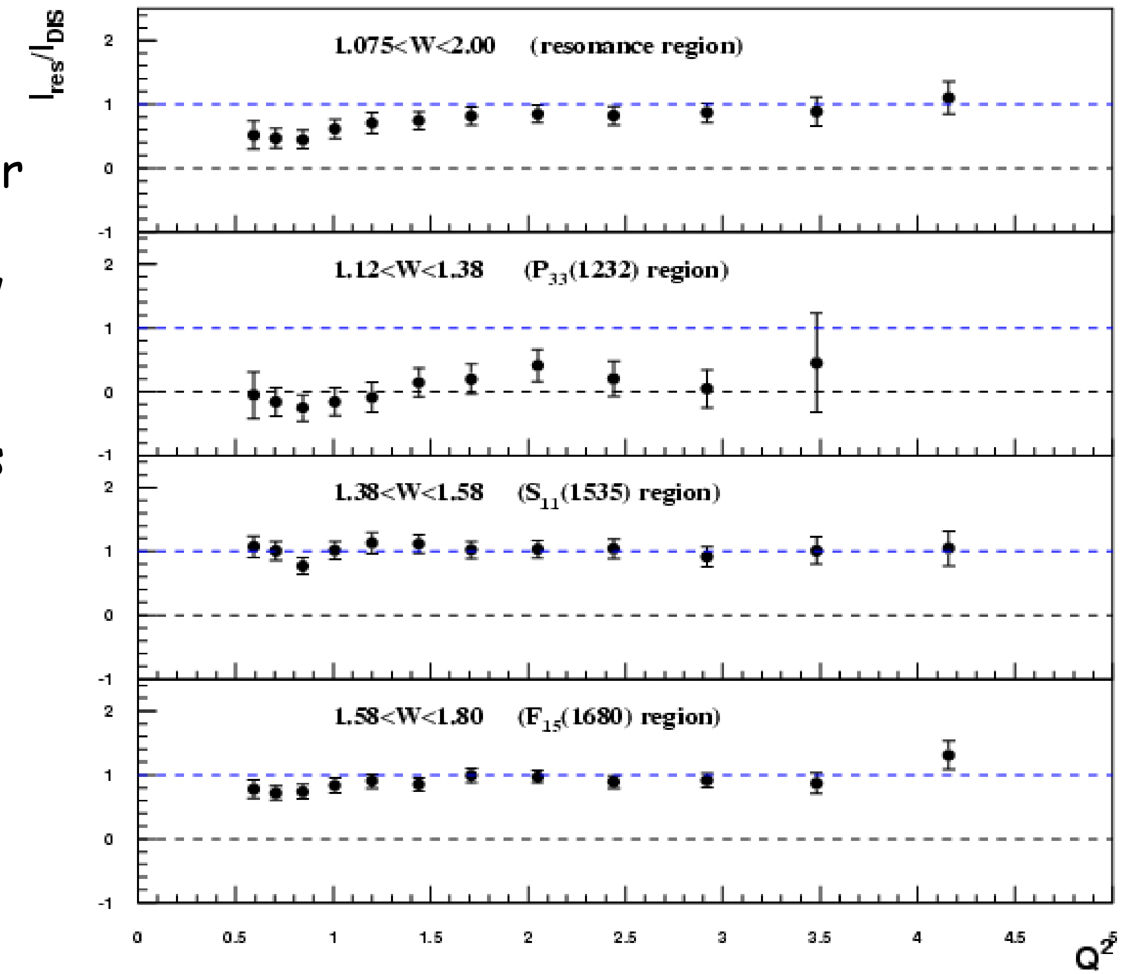


Global duality established down to ~1.5 GeV^2.

Local duality holds for second and third resonance region down to low Q^2.

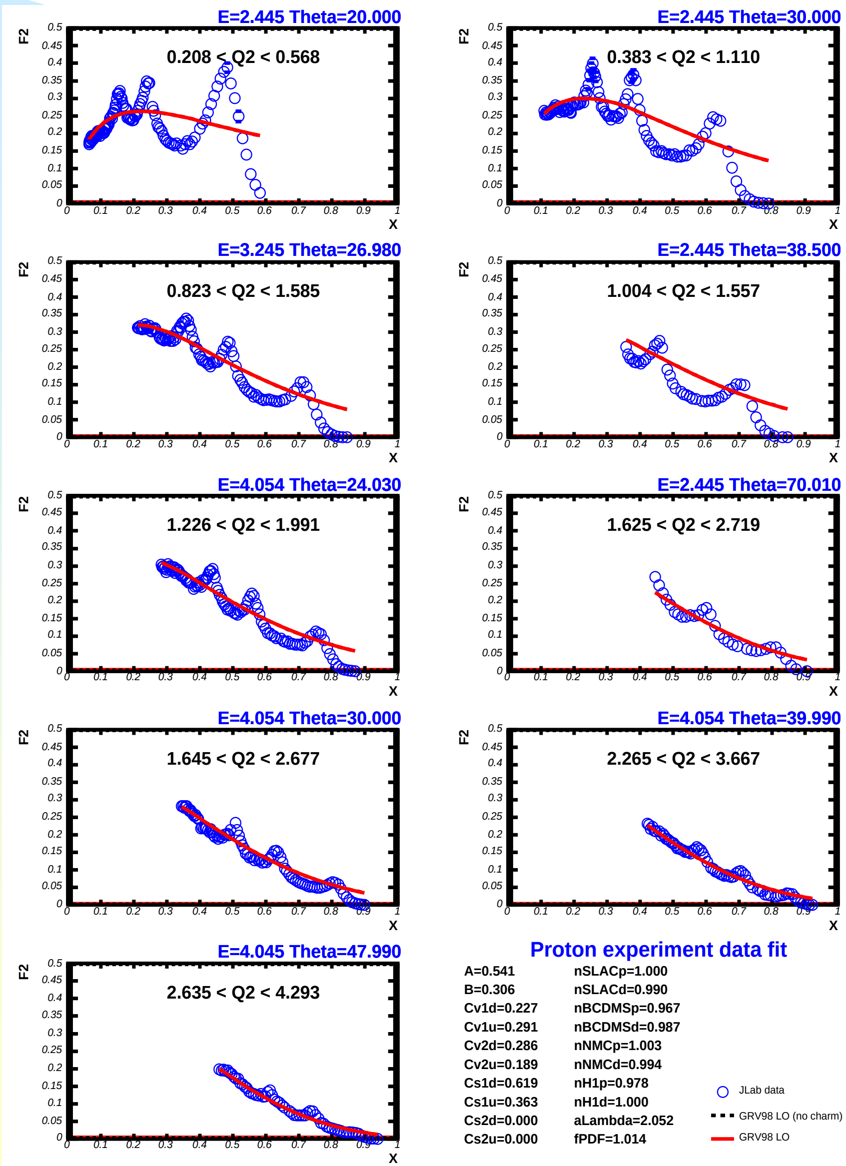
Spin Duality for the Proton

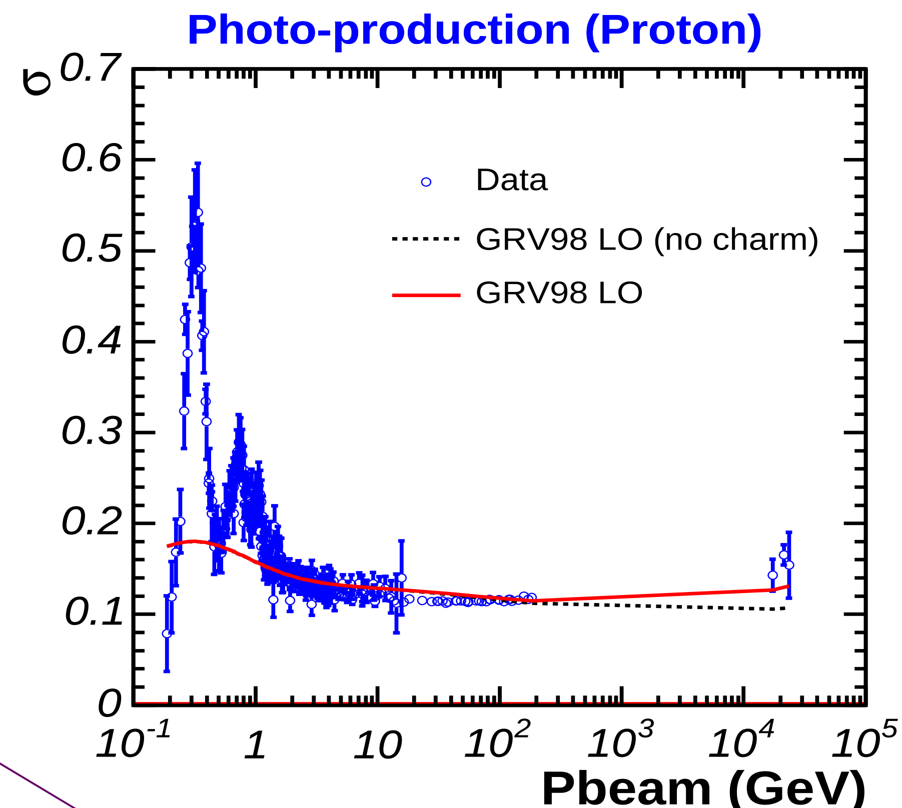
Eg1b very preliminary



As for deuteron, local duality works very well for 2nd and 3rd resonance regions, down to quite low Q^2. Doesn't work for the Delta(1232) region, although trend is towards unity at higher Q^2 . If paired with elastic, approaches unity from above rather than from below (work in progress).

Low Q^2 Too! Even Down to Photoproduction





Bodek and Yang duality-based model works at all Q^2 values tested - DIS to photoproduction!

Input for next generation neutrino experiments

Currently....

- Duality holds for all
  - Spin-averaged structure functions
  - Tested spin structure functions
- Duality observed in Nuclei
- Duality in semi-inclusive meson production (Ent talk)
- Works in photoproduction as well

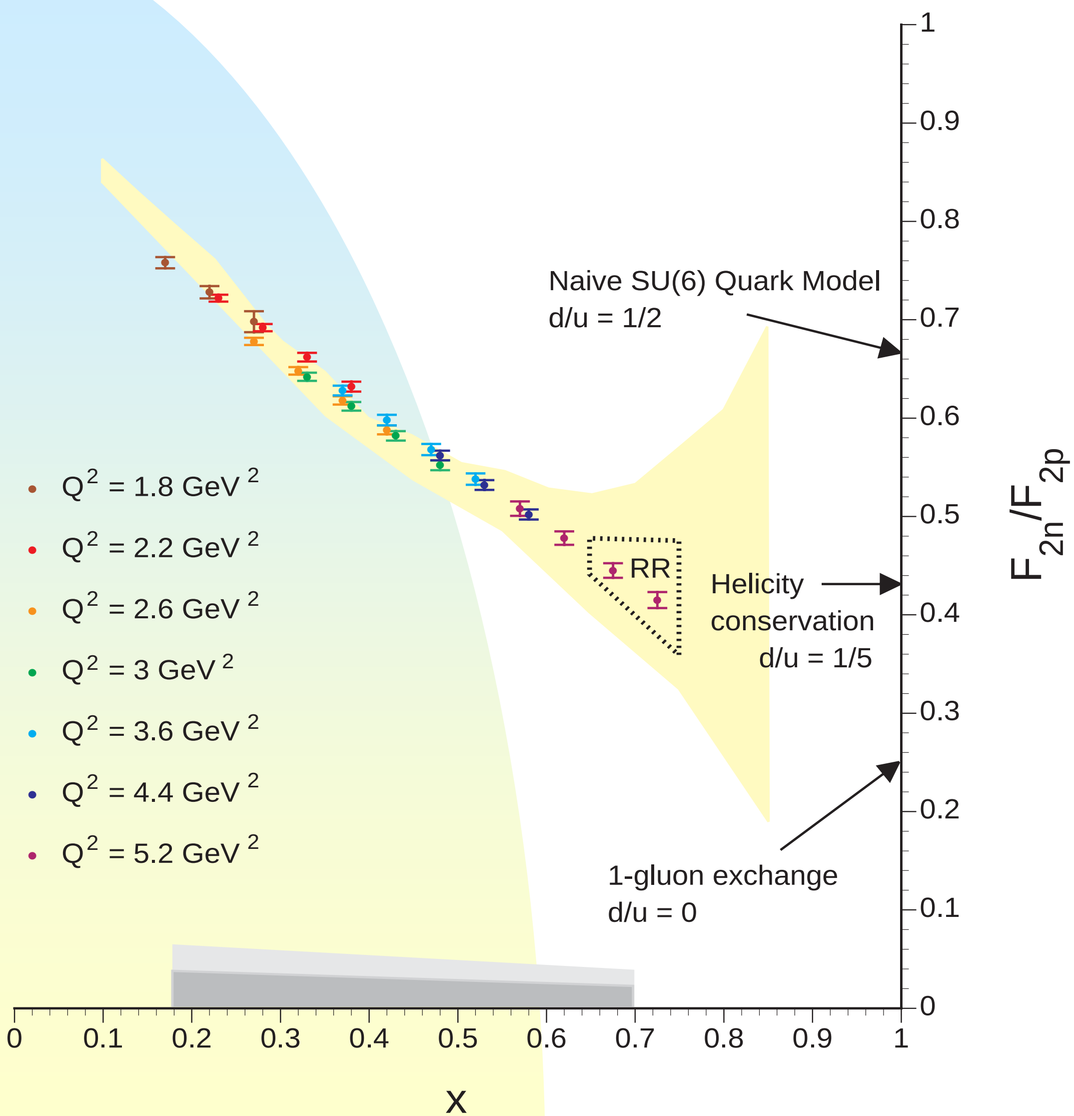
Appears to be a non-trivial property of proton structure!

What about the future?

- Continue semi-inclusive measurements, include kaon (Hall C E01-108)
- Continue spin structure measurements (results still expected from all JLab halls)
- L/T separated nuclear structure functions (Hall C E02-109, E04-001)
- Test the neutron (BONUS)
- Test in neutrino scattering (FNAL MINERνA)

- Major thrust of the JLab 12 GeV program
- Tool to access large x regime (LHC, Drell-Yan, *many other implications…)

F_2^n / F_2^p (d/u) Ratio at Large x – Projected Results



- Yellow shaded area represents current theoretical uncertainty
- RR data begin the Resonance Region
  ($W^2 > 3$ GeV^2, $Q^2 \sim 5$)
- Gray shaded areas represent systematic uncertainty
  - Light = total
  - Dark = normalized, point-to-point

“It is fair to say that (short of the full solution of QCD) understanding and controlling the accuracy of quark-hadron duality is one of the most important and challenging problems for QCD practitioners today.”

M. Shifman, Handbook of QCD, Volume 3, 1451 (2001)